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AN APPROACH FOR THE INTELLIGENT ASSESSMENT OF FUTURE TECHNOLOGY PORTFOLIOS

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ABSTRACT

A solid business case is highly dependent upon a strategic and intelligent technology research and development plan, or portfolio, in the early phases of product design. The embodiment of a strategic technology development plan is the identification and subsequent funding of high payoff technology areas that can maximize a company's return on investment, which entails both performance and economic objectives. This paper describes an approach whereby the high payoff technology areas may be identified to quantitatively justify resource allocation decisions and investment opportunities to meet future organizational goals. The approach includes the simulation of the impact of generic technology areas and the degree of difficulty of technological advances within said areas. The approach results in a dynamic forecasting environment whereby rapid trade-offs can be performed in the conceptual phases of design. This environment allows for intelligently building a successful technology portfolio to facilitate a quantitative justification of a solid business case. A proof on concept application was performed on a next-generation supersonic transport.

MOTIVATION

The design and development goal of an organization's new product is to deliver a superior system relative to the current state of the art. The drivers for the new design are to gain market share over a competitor, to provide increased capability for future threats, to respond to various societal needs, or to comply with government regulations. To accomplish this end, significant technical advances over the current state of the art capabilities must be pursued and infused to the end product. Despite this fact, aerospace manufacturers and operators are generally reluctant to adopt significantly advanced technologies, beyond those that are incremental improvements or imposed by regulation. Since economic incentives and the bottom line profit drive manufacturers and operators, evolutionary or incremental improvements in existing technologies are preferred in order to minimize investment costs and program risk [1]. However when taking this approach, Bandte notes that off-the-shelf technologies (or incremental improvements) are "readily available for implementation in the system, yet may be obsolete when the system is actually fielded."[2] In general, commercial aerospace systems require 7 to 15 years from concept formulation until the product launch date [3]. Thus, "a product using current technology to satisfy today's customers may have little appeal when it appears for sale"[4] at the product launch date as a result of technology obsolescence. In military systems, technology obsolescence is a major challenge due to the fact that the average acquisition time is 16 to 18 years [5]. Bandte also observes that "new technological solutions have to be found, applied to the components, and incorporated into the system."[2] This must be considered in the beginning phases of design when the business case is being determined. Otherwise, the impact of adding technologies in the later phases will require a redesign of the existing system and significant cost implications. Thus, potential technologies, or technological areas, must be considered concurrently with the product design when the business case is being finalized to avoid obsolescence at product launch and ensure long-term competitiveness.

Strategic Planning

To achieve this objective, a solid strategic plan must developed and guide the decision-making process for all program initiatives and spending ventures. "Strategic planning can be defined as a structured process through which an organization translates a vision and makes

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fundamental decisions that shape and guide what the organization is and what it does."[6] The strategic plan is then compiled into a decision package, in the form of a business case or project request, to justify capital project endeavors. A solid plan includes documentation and quantitative analysis that support the proposed investment opportunities, especially with regards to technology development programs.

Unfortunately in the aerospace industry, traditional methods of investment in technology development programs, or closing the business case, are ad hoc and lack rigor. "Many Research and Development (R&D) selection techniques have been developed in the last 30-40 years, but few have been used by R&D companies in industry. In fact, the methods used aren't much more advanced than two or three decades ago, even though the state of the art has advanced rapidly."[7] Cetron observes five typical approaches to allocating R&D resources for technology development plans [8]:

1. *Squeaking Wheel*: cut resources from every area and then wait and see which area complains the most. Based on the loudest and most insistent, then restore budget until ceiling is hit.
2. *Level Funding*: budget perturbations minimized and status quo maintained across areas.
3. *Glorious Past*: "once successful, always successful". Assign resources solely on past record of achievement.
4. *White Charger*: best speaker or last person to brief the boss wins the money or whichever department has the best presentation.
5. *Committee*: a committee tells the decision-maker how to allocate resources.

Cetron points out that the scientific and objective foundations of these approaches are lacking and naïve, but widely used. Thus, the business case that is developed is lacking in substance and strongly suggests the need for a means by which more informed, substantiated decisions can be made. Froham comments that most R&D technology developments are allocated resources based on past activities, "glorious past" approach, in the specific research area rather than the potential bottom line contributions to the competitiveness of the end product [9]. In fact, short-term funding tends to be the driver for allocating resources which leads to projects and endeavors that are not broader-range or do not have long-term or high payoffs for the particular company [9].

Thus, a need exists within industry, and government, to have a capability to identify high payoff technology areas with minimal investment and resource expenditure to intelligently direct R&D resources for technology developments. This need must be fulfilled without pursuing specific technology developments. Therefore, to create a successful project plan of which results in a solid technology portfolio, a means to quantitatively forecast the potential impacts of various technology areas to new or derivative products must exist. The focus of the current research is to describe an approach that could fulfill this need.

<u>Forecasting Techniques</u>

The primary purpose of forecasting, in any context, is to provide the decision-maker with adequate information on which future decisions, company strategies, and business cases may be based. Technology forecasting is a prediction of the future characteristics of useful machines, procedures, or techniques [10]. "Technology forecasting started in 1959 with Ralph Lenz's Master's thesis. Only in the late 1960's did it get attention due to attempts to control the mushrooming growth and planning in R&D."[11] Forecasting provides a better quantitative view of the future and the evolutionary path to be followed so as to lead to more informed decisions and provides a means of estimating the risks associated with a project [4].

Two broad categories of forecasting exist: exploratory and normative. Exploratory forecasting techniques consider historical trends and extrapolate into the future to predict what may happen. "The feasibility of this process depends upon an assumption that progress is evolutionary and does follow a regular pattern."[4] In essence, exploratory forecasting asks the question: *With the specific technologies that are being developed within the organization today, how will the end product compare to the design specifications of the future or compete with future systems?* Application of this approach depends upon the assumption that the progress of a technology will be evolutionary and the R&D funding will be continuous [4]. An approach of this nature was created by Kirby [12] for specific technology assessments in aerospace systems and is called the Technology Identification, Evaluation, and Selection (TIES) method. This is approach is applicable when an organization has an existing portfolio and desires an assessment of the capabilities of the technologies within that portfolio. This approach assists in the identification of the high payoff technologies currently funded within the organization.

The normative method begins with future goals and works backward to identify the levels of performance needed to obtain the desired goals, if at all achievable with the resources available. This approach asks the question: *What technology developments should be pursued by the organization today to meet or exceed the design specifications or system requirements of the future?* This approach was also formalized for aerospace applications and is called the Technology Impact Forecasting (TIF) method [13,14]. The TIF method establishes how much improvement is needed from the various technical disciplines to meet or exceed future customer requirements. The current research seeks to expand on previous applications of the TIF method to introduce more complex and realistic trade-offs that surface within various technology areas.

APPROACH

The TIF method has been applied to numerous vehicles, including subsonic [13,14] and supersonic transports [15], rotorcraft [16], and military systems [17]. In each application, the description of the steps required for implementation has varied slightly and morphed in the actual steps for implementation. However, common elements exist through each for execution. The steps including defining the problem, evaluating system technical feasibility and economic viability, infusing new technologies, and assessing the robustness of the best solutions. Overviews of the steps are briefly described herein.

Overview of TIF

The first step in any method is to define the problem at hand as driven by a societal need or military threat in terms of a set of customer requirements. Once the need is established, the customer requirements must be mapped into some mathematically quantifiable terminology. This terminology is in the form of system product and process parameters, referred to here as system metrics. System metrics are standards of measurement used to judge the goodness of the system, equivalent to a figure of merit. Next, a potential class of vehicle concepts is identified that may fulfill the customer requirements and a datum established. Subsequently, a design space, as bounded by control variables such as wing aspect ratio, engine thrust, etc., is defined as deviations from the baseline. This space is investigated for technical feasibility in a Modeling and Simulation environment via the Response Surface Methodology (RSM) combined with a Monte Carlo Simulation. Next, an economic space is investigated with variations in noise variables, such as fuel cost and return on investment, to determine the economic viability via the same approach. If the probability of success for feasibility and viability are unacceptable, the decision-maker has the option to expand the design space further, relax the constraints, investigate other vehicle concepts, or infuse new or alternative technologies. For the purposes of the TIF method, the later option is pursued through a simulation of technology metrics. A technology metric is a standard of measurement used to define the impact of a generic technology area (or a specific technology if applying the TIES method) on the system and includes benefits and degradations. The system technical feasibility and economic viability are explored again. If feasible and viable solutions exist, the robustness of the best solutions can be evaluated with various techniques. One method is the Robust Design Simulation and has been implemented for various concepts [18,19].

Enhancements to TIF

The focus of the current research is to expand on the previous applications and existing TIF method. Specifically, more realistic aspects of infusing new technologies will be addressed and clarification of some issues that were not presented adequately in previous efforts. In particular, the following will be addressed and implemented for the proof of concept:

- discussion of the need of a cohesive Modeling and Simulation (M&S) environment to facilitate a quantitative business case
- explanation of how one mimics a generic technology impact within a M&S environment, what is required within that environment, and visualizing the impacts of technology areas
- discussion of technology developments and how to simulate when no specific technologies exist
- simulation of the degree of difficulty of technology area developments and how that plays a role in the determination of the most significant technological areas to pursue for the technology portfolio

Modeling and Simulation

In the conceptual stages of product design, a rapid assessment is desired so that trade-offs can be performed with minimal time and monetary expenditures. The advent of the computer has greatly facilitated this objective via M&S environments. The Defense Systems Management College defines a model as “a physical, mathematical, or logical representation of a system entity, phenomenon, or process”; while a simulation is “the implementation of a model over time…and a simulation brings a model to life and shows how a particular object or phenomenon will behave.”[20]

Most companies have an in-house developed M&S environment to perform the design trades. However, *the TIF method is not code specific or system specific*, but, the M&S tool utilized must have some basic features as outlined in References [12,21] and include: physics based analysis, unconstrained mission analysis, economic analysis capability, and a means to simulate incremental changes in disciplinary metrics. One cannot underestimate the importance of having a cohesive M&S environment. Without this environment, application of the TIF method is arduous and would be qualitative in nature. The lack of a cohesive M&S capability would defeat the purpose of building a solid business case and default to traditional approaches for R&D resource allocation. A principle requirement for any decision making process is the ability to quantitatively assess the customer requirements that drive a design to justify the business case. This can only be achieved through an M&S environment. In fact, the Defense Systems Management College states that use of an M&S environment provides four benefits to the design process and includes cost savings, accelerated schedule, improved product quality, and cost avoidance [20].

Simulating Technology Impacts

Since advanced technology concept areas will be infused to the system of interest, a capability must exist to quantify the technology impacts. Furthermore, higher fidelity tools such as finite element methods and computational fluid dynamics can not always capture the physics associated with a new technology. A standard practice for modeling technologies in the aerospace industry is through incremental changes in disciplinary metrics such as drag, component weights, and fuel consumption within an M&S environment. The incremental changes simulate the discontinuities associated with the addition of new technologies. Thus, to model the incremental changes of the technical disciplinary metrics, a multiplicative factor, denoted as “k” factor or technology impact factor, on those metrics must be added within the M&S environment. Most analysis tools already have these factors built into the source code as calibration factors. However, if the factors are not inputs to the analysis tool, the internal logic must be modified such that the factors can be input directly. Subsequently, the technology metrics are determined through brainstorming exercises of potential technology areas or disciplines and appropriate ranges established. The ranges must capture potential benefits *and* degradations to system. Some of the more notable metrics include component weights, drag, fuel flow, thrust, cycle parameters, engine efficiencies, subsystem weights, and economic parameters. Through system decomposition exercises, most specific technologies that could be developed could be mapped to many of the technical metrics.

The impact of technology metrics on the system metrics can be assessed quantitatively through a linear or higher order sensitivity analysis and formulated in a metamodel. A metamodel formulation is facilitated by the Response Surface Methodology (RSM). The reader is referred to Reference [22] for more information on the theoretical aspects of RSM. A powerful commercial software available for implementing the RSM is the SAS Institute’s package called JMP®[23]. With the Prediction Profile feature of JMP®, the analysis of the resulting metamodel can be visualized as in the example depicted in Figure 1. The prediction profiler depicts the *prediction traces* for each impact of the independent technology metrics. The prediction trace is defined as the predicted response in which one variable (or technology metric) is changed while the others are held at their current values. The profiler shows the sensitivity of the system metrics to the technology metrics. In the dynamic environment, moving the vertical hairline with the mouse varies the impact of a technology metric and JMP® recomputes the underlying metamodels and updates the prediction traces and values. The power of depicting the sensitivity representation in this fashion is the ability to instantaneously show the interactions of the technology areas and with the system metrics. This is extremely useful in *providing the decision-maker a visual means by which informed decision can be made and investment decisions justified*. This result of the visualization has been the heart and soul of previous TIF method applications and is called the TIF environment. If a technology metric, or “k” factor, is shown to improve the system metrics, that technology impact can be identified as worthy of further investigation and an actual technology could be identified which could provide the technology metric projections.

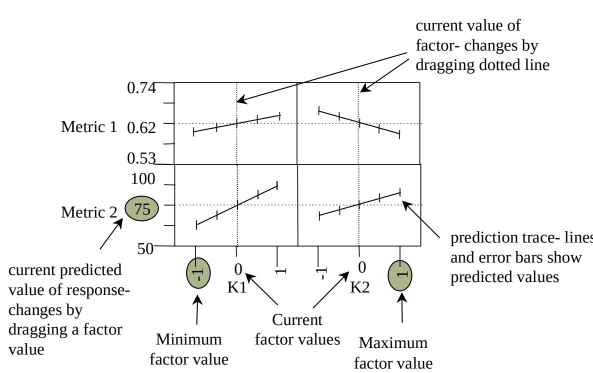

Figure 1: Example Dynamic TIF Environment

Technology Development

One aspect not considered with previous applications of the TIF method includes the level of maturity of various technological areas. Albeit, this subject was breached with the TIES method, as described by Kirby [12]. However, when an organization is building a business case, the details of the level of maturity of a particular technology are not known. Thus, one desires to simulate the level of maturity of a technological area rather than a specific technology development program. To accomplish this end, one must consider the process through which technology areas evolve through time.

"No single growth pattern describes the development and diffusion of all technologies. There are general concepts of how technologies develop, however, and these can be a useful guide."[24] One of the prominent concepts is through the *method of analogy* to other well-known physical or biological systems [25] such as growth patterns of yeast cell populations. Historical data for various technology concepts, including speed, steam engines, and fluorescent lamps [26], has revealed an ordered pattern of development that resembles this biological growth curve, also known as a sigmoidal curve or an S-curve. The method of analogy assumes that a technology development program will typically follow this S-curve pattern if one were to track the evolution through time. The most notable example is the historical progression of travel speed, as a fraction of Einstein's speed of light as shown in Figure 2. Starting with the pony express and progressing to space flight, one can observe that speed has advanced steadily from history through various technological innovations. The upper limit of this curve is typically viewed as a physical limitation of the functional capability of the technology or technology area and in most instances, a point of diminishing returns. In this example, the upper limit is the speed of light.

One may investigate each contributing element of the speed versus time growth trend and find an upper limit exists for each generation. For each generation in the speed trend, one cannot surpass, within the current bounds of the physics imposed, its own natural limit. For example, there is a leveling of the individual trends in Figure 2. Trains can only reach a certain top speed with the existing power plants and rail systems within which they are utilized. Air breathing aircraft are limited to particular speeds due to gas turbine engine operational limits and drag rise impacts. There exists a point at which the physical limit for one generation of a concept is surpassed due to the occurrence of a technological breakthrough.

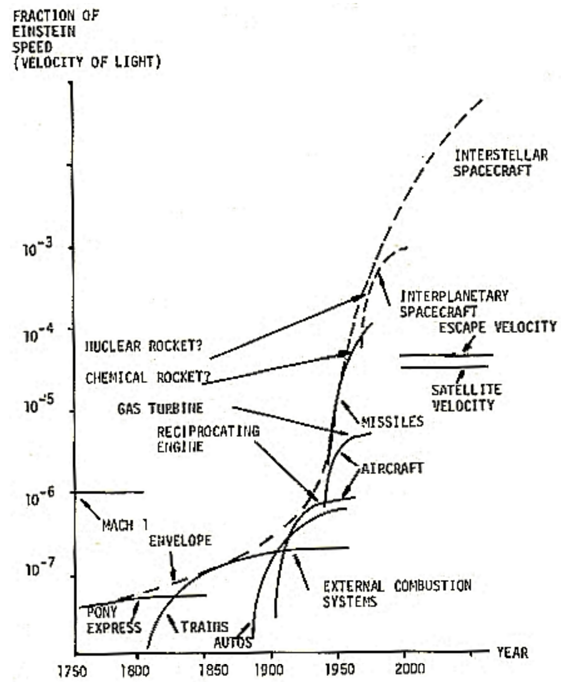

Figure 2: Vehicle Speed Variation with Time [26]

The concept of a breakthrough in physics to surpass a given physical limit is depicted in Figure 3. The maximum level of a given technology is essentially the natural limit of the benefit. This implies that the maturation variation with time remains constant. When this limit is reached, there is no other alternative but to pursue a new technological idea that reaches beyond the current limits and design practices. However, incremental improvements at the top of the growth curve are rather simple to achieve. If one were on the steep slope of growth, significant developments are required to continue the progression. That is, the degree of difficulty of achieving particular improvement value becomes more arduous. The importance of these ideas is extremely relevant when building a business case based on required improvements needed from various technological areas. If one were to determine that a certain benefit was required from Technology A and the current capabilities of that technology area were near the physical limit, one could infer that the potential to exceed the natural limit might occur. Thus, the level of benefit from Technology A may never be achieved. This would imply that a technological breakthrough was required to transition to another growth curve (Technology B) that had a higher physical limit to allow for growth potential and meet the required levels of benefit. At present, there is no capability to determine where this natural limit occurs. However, research is being conducted to investigate potential avenues for quantifying this phenomenon.

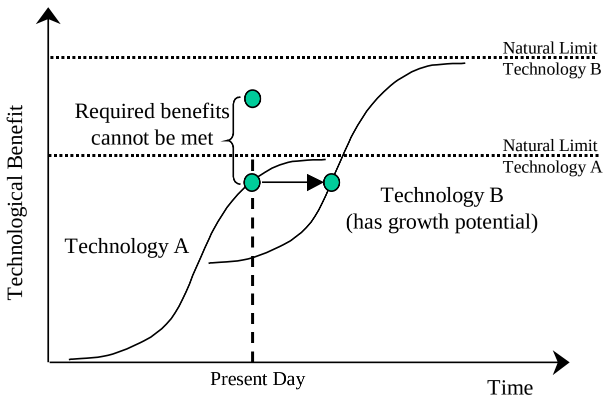

Figure 3: Technology Progression [4]

Technological Degree of Difficulty

The point at which one resides on the growth curve is also compounded by the degree of difficulty of traversing the curve. The higher the degree of difficulty, the higher the technical risk and potential for failure. Thus, one must consider the degree of difficulty in achieving a particular technology development goal when building a technology portfolio. If a particular improvement is required to obtain technically feasible solutions with one technology metric that has a high degree of difficulty; one might pursue an alternative technology area that had a lower degree of difficulty to reduce the organization's investment risk. A potential approach for inclusion of these ideas evolved from research proposed by Mankins. Mankins suggested a degree of difficulty scale, similar to NASA's Technology Readiness Levels (TRL), to capture this aspect and is called the Research and Development Degree of Difficulty (R&D^3) [27]. The R&D^3 metric is a subjective measure of how much difficulty is expected to be encountered in the maturation of a particular technology. Unlike typical risk factors of high, medium, and low, the R&D^3 is an intelligible description of the difficulties that must be overcome to develop a particular technology. The R&D^3 scale is complimentary to the TRL metric and consists of five levels varying from a Level I (low degree of difficulty) to a Level V (very high degree of difficulty). Above a Level II, alternate approaches should be pursued in order to assure a high probability of success in achieving technical objectives. Each of the levels are described herein [27].

R&D^3 – Level I: A very low degree of difficulty is anticipated. A *simple* interpolation or a *modest* extrapolation of an existing capability is required.

R&D^3 – Level II: A moderate degree of difficulty should be anticipated. A *significant*, but not extreme, extrapolation from some existing capability or a modestly new capability is needed.

R&D^3 – Level III: A high degree of difficulty anticipated. A *very significant* extrapolation from some existing capability or a *significantly new* capability is needed.

R&D^3 – Level IV: A very high degree of difficulty anticipated. Multiple technological approaches need to be pursued. A *dramatic* extrapolation from some existing capability or an *extremely new* capability is needed.

R&D^3 – Level V: The degree of difficulty anticipated is so high that a crucial breakthrough is required in physics, chemistry, or some other & principle. Basic research in essential areas needed before feasible system concepts can be refined.

IMPLEMENTATION

The new aspects of the TIF method described herein were applied to a High Speed Civil Transport (HSCT). This concept has received worldwide attention since its renewed interest in the commercial industry in the mid-1980's. This vehicle was a perfect test-bed for the proof of concept due to the technically challenging customer requirements and the need for revolutionary advances over present day capabilities. The results from in References [12,14] are utilized herein and presented when needed for clarity. The configurations analyzed in this study were sized for a 5,000 nm mission with the primary cruise altitude of 67,000 ft at Mach 2.4. A subsonic cruise portion preceded the primary cruise segment at an altitude of 35,000 ft at Mach 0.9. The payload was assumed 300 passengers with baggage and a flight crew of two, nine flight attendants, and a fuselage length of 310 ft with a maximum diameter of 16 ft. The critical metrics by which system feasibility was measured are listed in Table I.

Table I: HSCT System Metrics

Metric	Acronym	Constraint Value	Units
Approach Speed	Vapp	≤ 106	kts
Stage III Flyover Noise	FON	≤ 155	EPNLdb
Landing Field Length	LdgFL	≤ 11,000	Ft
Stage III Sideline Noise	SLN	≤ 103	EPNLdb
Takeoff Field Length	TOFL	≤ 11,000	Ft
Takeoff Gross Weight	TOGW	≤ 750,000	lbs
Avg Required Yield per Revenue Passenger Mile	$/RPM	≤ $0.10	FY96 $M

The HSCT design space exploration performed in References [12,14] revealed that more than 50% of the design space considered could meet the LdgFL and TOGW requirements. The TOFL, Vapp, and FON could only be satisfied by 19.5%, 3.5%, and 2.5%, respectively. The concept technical "show-stopper" was the SLN, which could not satisfy the 103 EPNLdB requirement with any combination of design parameters and required at least an 8.8% improvement in noise characteristics to obtain a 25% feasible design space. Since noise levels are measured in decibels, an 8.8% improvement was a significant required improvement. Since no feasible design space existed, the economic viability was not investigated and technology areas were infused and included 16 technical metrics.

For brevity, only the five significant contributors to the system metrics were used and are listed in Table II. Although the remaining 11 technical metrics were important for a realistic TIF application, a smaller scale problem was desired. The "0" implies no change in the technical metric (i.e., present day levels of technologies), while a negative denotes a reduction and a positive an increase. The engine weight was considered to be a significant metric since previous studies have indicated a technology that will suppress noise levels will increase the engine weight. Based on the five technology areas and ranges, the RSM was utilized to create second order metamodels of the system metrics as a function of "k" factors, as listed in Table II. The resulting metamodels were visualized in JMP® (TIF environment) to determine the required levels needed from each technical metric to create a feasible and viable solution as shown in Figure 4.

Three important aspects of information may be obtained from the TIF environment. First, one can evaluate how much fidelity is required in an analysis tool to model a technology. For example, assume that the noise levels were not a constraint. If some arbitrary technology affected the suppression levels, a lower fidelity analysis code could be used to predict the noise suppression impact on the other performance metrics due to small prediction trace slopes in Figure 4. However, a higher fidelity analysis code should be used to quantify the supersonic drag to due the higher sensitivity of the system metrics to this technology area. The slope of the prediction traces informs the decision-maker which "k" factor values need to be "nailed" in the analysis to minimize the influence of code fidelity to the technological uncertainty. Also of importance is the effect that degradation in technology performance would have on the system throughout the operational life. For example, assume an arbitrary technology was infused to suppress the noise levels and was designed

Table II: Significant Technology Areas Infused to an HSCT Concept

Technical Metric "k" Factors	Minimum (%)	Maximum (%)
Wing Weight	-35	+7
Fuselage Weight	-40	0
Engine Weight	-10	+46
Noise Suppression	-21	0
Supersonic Drag	-24	0

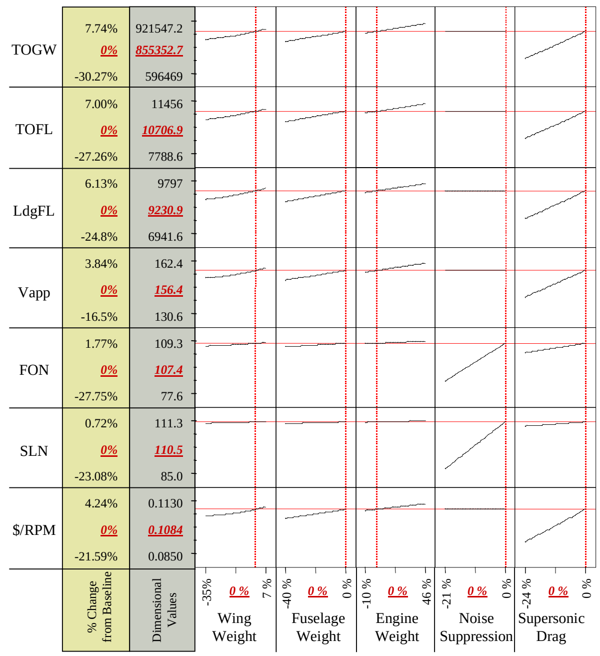

Figure 4: TIF Environment for an HSCT

for a specific value. If the ability of that technology to suppress the noise were to degrade rapidly over the life of the vehicle, the noise constraints might not be met as the technology degrades due to the large sensitivity of SLN and FON. Finally, the Prediction Profilers of the TIF environment may be interpreted as a dynamic forecasting environment. For example, the SLN was a performance "show-stopper" for an HSCT concept. As is evident, a technology that suppressed the noise had the largest impact on the SLN, while the supersonic drag reduction had the largest influence on all other metrics. One may reverse engineer the problem and determine the required levels of improvement for each technology area and set goals for specific technology development programs to meet those goals. As is evident, a feasible solution does exist with some combination of the technical metrics due to the lower bound values of the system metrics exceeding the constraint values listed in Table I.

The metamodels of the system metrics were "reverse engineered" to determine the minimal amount of improvement required from each technical metric to satisfy the constraint values. As a result, the following improvements were required from a conventional baseline: wing weight of –26.6%, fuselage weight of –12.3%, engine weight of +15.6% (to account for improvements in noise), noise suppression of -5.778%, and supersonic drag of –8.28%. The three primary system metrics of interest were the TOGW, SLN, and $/RPM, which were the more critical of the original set and were typically the active constraints.

A cross section of the technology space created by the technology metrics considered is depicted in Figure 5 as a Contour Profiler. The Contour Profiler is another interactive feature of JMP®. The metric indicative of improvements in structures (wing weight) is compared to the variations in aerodynamics (supersonic drag). The active constraint in this dimension of the technology space is the TOGW. The baseline configuration and the minimum feasible solution are identified. One can immediately visualize the amount of improvement needed from each technical area from the vector located at the baseline to the feasible area. As is evident, one could obtain a feasible solution for numerous paths and combinations of the technical areas. One possible approach for determining which path to take is through inclusion of the degree of difficulty of advancing technology area improvements on a particular path.

To account for the degree of difficulty to advance a technology area, one must map Mankin's qualitative R&D^3 levels to a quantitative scale for evaluation purposes as listed in Table I and denoted by the factor α. If a technology metric had a target value of a 35% improvement, the difficulty the technology area will encounter varies on the level of research conducted previously in that area and what is potentially required to reach that goal. The variation in R&D^3 could be mathematically expressed to the desired level of the technology area improvement as depicted in Figure 6. The slopes of the different R&D^3 curves could be indicative of where the current capabilities exist on a technology area S-curve. For example, the exponential curve is representative of the current value of a technical metric being at or near the upper limit of the S-curve. Thus, minute improvements are very difficult until some breakthrough occurs and, thus, the R&D^3 levels off. However, the R&D^3 value remains high since one is forecasting the potential advances of a technological area, which is extremely difficult.

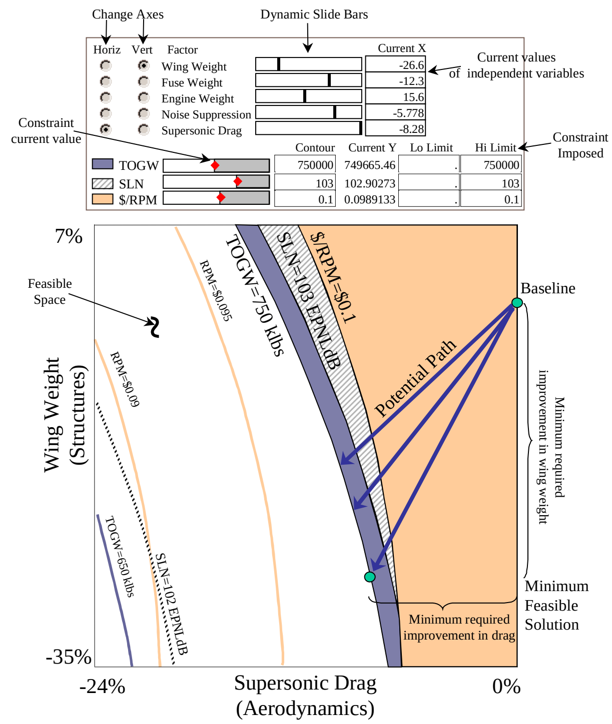

Figure 5: Potential Paths for Feasibility

Table III: Defining R&D^3 Levels Quantitatively

Qualitative R&D^3	Mapped R&D^3 Scale (α)
Level I	0.1
Level II	0.4
Level III	0.7
Level IV	0.9
Level V	1.0

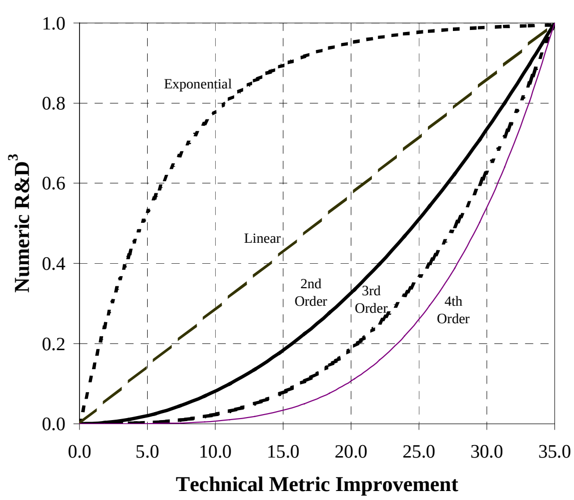

Figure 6: Potential R&D^3 Paths for Improvement

The numerical R&D^3 scale was incorporated to four of the technical metrics: wing weight, fuselage weight, supersonic drag, and noise suppression. For each metric, the maximum improvement was considered the upper or physical limit for each area. Although this is not justified mathematically, the values were assumed for implementation purposes until a theoretical approach can be developed. Four R&D^3 trends were assumed for each metric as a function of the metric upper limit as summarized in Table IV and depicted as normalized values in Figure 7. The noise suppression was considered to have an exponential increase in the R&D^3 value due to the significant effort required to achieve more than a few percentage points reduction. However, once the difficulties of the physics are overcome, the R&D^3 variation should remain relatively constant. As for the supersonic drag improvements, a moderate level of difficulty would be necessary to achieve 10-15% reduction from present day levels. However, a 24% reduction was significant for a supersonic transport and the quadratic function for the drag R&D^3 was assumed. The R&D^3 values for the minimal feasible solution were: wing weight of 0.44, fuselage weight of 0.3075, supersonic drag of 0.08, and noise suppression of 0.685.

A total degree of difficulty was assumed as a linear combination of the four technical metric R&D^3 functions. The total R&D^3 was calculated based on the same RSM applied to create the original TIF environment. Based on the minimal feasible solution obtained earlier, the technology space was investigated via the Contour Profiler, Figure 8. An upper limit to the total R&D^3 was assumed 0.5. This would translate into a company investing in a risky technology area beyond the typical incremental or evolutionary changes pursued. For the minimal feasible solution, the total R&D^3 was 0.378 which would translate to a combined degree of difficulty of a Level II to achieve the technical metrics. Again, multiple paths appear to exist to achieve a feasible solution. One could move to a lower total R&D^3 and achieve a feasible solution within this cross section of the technology space. However, consideration must also be given to the other dimensions of the technology space. The variation of the feasible space of the cross section of noise suppression (propulsion system improvements) with the supersonic drag (aerodynamic improvements) is depicted in Figure 9. As is evident, minimal paths existed for a feasible solution within this dimension. However, this space was constrained since the other technology metrics were held constant in this cross section. If the weight reductions were to change, the feasible space options would also change.

Table IV: Technology Area Functional R&D^3

Metric (k)	R&D^3 Level (α)	β	Max Δk	R&D^3 Function
Wing weight	V (1.0)	3	-35%	$\alpha \dfrac{k^{\beta}}{\max\_\Delta k^{\beta}}$
Fuselage weight	V (1.0)	1	-40%	$\alpha \dfrac{k^{\beta}}{\max\_\Delta k^{\beta}}$
Supersonic drag	IV (0.9)	2	-24%	$\alpha \dfrac{k^{\beta}}{\max\_\Delta k^{\beta}}$
Noise suppression	V (1.0)	0.2	-40%	$\alpha - [\exp(k)]^{\beta}$

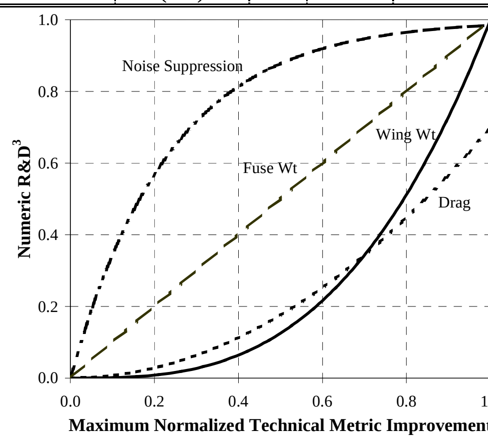

Figure 7: Numerical Degree of Difficulty

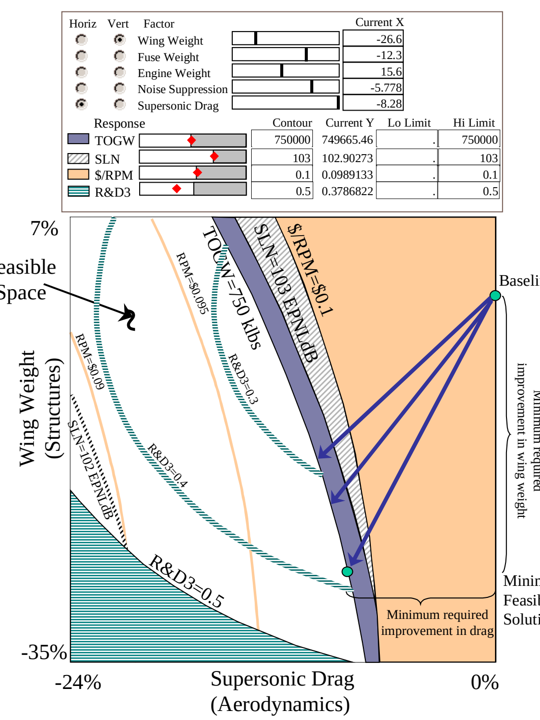

Figure 8: Potential Paths for Feasibility Including R&D^3

In the dynamic environment of the Contour Profiler, the wing weight and the supersonic drag were adjusted to minimize the total R&D^3 value from Figure 8; a new feasible solution was obtained. The wing weight was modified to only a 5.9% reduction while the supersonic drag reductions increased to –12.43%. The corresponding values of the system metric did not change that significantly except for SLN which dropped from 102.9 to 98.1 EPNLdB; however, the system R&D^3 dropped significantly from 0.378 to 0.296. Consequently, the degree of difficulty associated with the wing weight improvements reduced from 0.44 to 0.005, while the supersonic drag increased from 0.08 to 0.188. The variation for feasible space between the two cross sections of the technology space depicted in Figure 9 and Figure 10 was indicative of the dynamic interactions of the technical metrics. However, inclusion of the degree of difficulty to progress a technology provided an added dimension upon which target values for improvement in the technology areas could be identified more efficiently. The better feasible solution identified from a reduction of the system R&D^3 value resulted in wing weight of -5.9% at 0.005, fuselage weight of –12.3% at 0.3075, engine weight of 15.6%, noise suppression of –5.778% at 0.685, and supersonic drag of –12.43% at 0.188. The required changes of the technology areas would become the target values for specific technology developments to pursue for the organization. Thus, the future business case could be closed since the technology portfolio was quantitatively justified.

CONCLUSIONS

This paper discussed a quantitative approach to identify the highest payoff technology areas to pursue when building a business case for future product developments. The research focused on a discussion of an existing method called Technology Impact Forecasting. The method was enhanced to capture the effects of technology maturity with respect to growth potential and the degree of difficulty of traversing a development trend. In particular, a quantitative degree of difficulty scale was introduced and applied to a supersonic transport to intelligently identify the needed improvements from various technical areas based on the difficulty of achieving the desired improvements to obtain a feasible solution. Application of this approach provided target values for technology area improvements such that specific technologies could be identified and pursued within the organization. The approach provided a quantitative justification of potential technology areas to direct R&D resources while minimizing the technical risk of achieving a feasible solution.

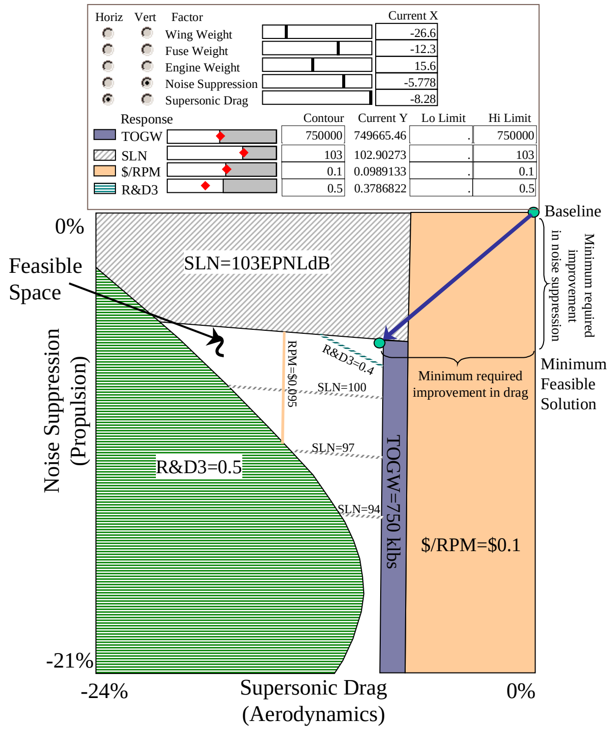

Figure 9: Limited Paths for Feasibility Including R&D^3

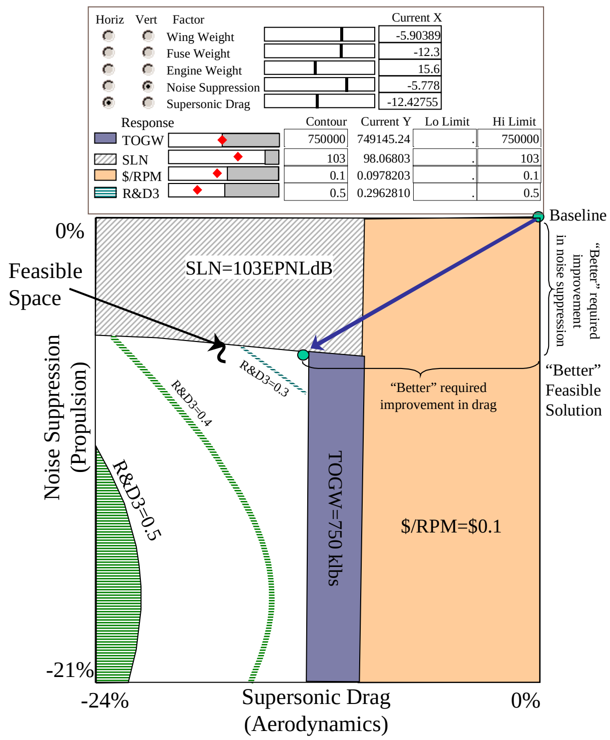

Figure 10: “Better” Feasible Solution Including R&D^3

REFERENCES

[1] National Research Council, "Maintaining U.S. Leadership in Aeronautics: Breakthrough Technologies to Meet Future Air and Space Transportation Needs and Goals," National Academy Press, Washington, D.C., 1998.

[2] Bandte, O., "A Probabilistic Multi-Criteria Decision Making Technique for Conceptual and Preliminary Aerospace Systems Design," Ph.D. Thesis, Georgia Institute of Technology, October 2000.

[3] Hartley, J.R., Concurrent Engineering, Productivity Press, Portland, OR, 1992.

[4] Twiss, B.C., Forecasting for Technologists and Engineers: A Practical Guide for Better Decisions, Peregrinus, London, U.K., 1992.

[5] Best Practices: Successful Application to Weapon Acquisitions Requires Changes in DoD's Environment, GAO/NSIAD-98-56, February 1998.

[6] Executive Guide: Leading Practices in Capital Decision-Making, GAO/AIMD-99-32, December 1998.

[7] Szakony, R., "So Many Projects, So Little Time: Improving the Selection of R&D Projects," Technology Management: Case Studies of Innovation, Edited by R. Szakony, Auerbach, Boston, 1992.

[8] Cetron, M.J., "Technology Forecasting for the Military Manager," An Introduction to Technological Forecasting, Edited by J.P. Martino, Gordon & Breach, London, 1972.

[9] Froham, A.L., "Making Book in R&D, Allocating Resources Effectively," Technology Management: Case Studies of Innovation, Edited by R. Szakony, Auerbach, Boston, 1992.

[10] Martino, J.P., Technological Forecasting for Decision Making, 2nd Edition, Elsevier, New York, 1983.

[11] Martino, J.P, "Foreword," An Introduction to Technological Forecasting, edited by Martino, J.P., Gordon and Breach, London, 1972.

[12] Kirby, M.R., "A Methodology for Technology Identification, Evaluation, and Selection in Conceptual and Preliminary Aircraft Design," Ph.D. Thesis, Georgia Institute of Technology, March 2001.

[13] Mavris, D.N., Mantis, G., Kirby, M.R. "Demonstration of a Probabilistic Technique for the Determination of Economic Viability," AIAA-97-5585.

[14] Kirby, M.R., Mavris, D.N., "Forecasting the Impact of Technology Infusion on Subsonic Transport Affordability," SAE Paper No. 985576.

[15] Mavris, D.N., DeLaurentis, D.A., "A Stochastic Design Approach for Aircraft Affordability", ICAS Paper 98-6.1.3.

[16] Mavris, D.N., Baker, A.P., Schrage, D.P., "Development of a Methodology for the Determination of Technical Feasibility and Viability of Affordable Rotorcraft Systems," 54th Annual Forum of the American Helicopter Society, Washington D.C., May 1998.

[17] Mavris, D.N., Soban, D.S., Largent, M.C., "An Application of a Technology Impact Forecasting (TIF) Method to an Uninhabited Combat Aerial Vehicle," SAE Paper No 1999-01-5633.

[18] Mavris, D.N., Bandte, O., Schrage, D.P., "Effect of Mission Requirements on the Economic Robustness of an HSCT Concept", 18th ISPA Conference, Cannes, France, June 1996.

[19] Mavris, D.N., Roth, B.A., "A Methodology for Robust Design of Impingement-cooled HSCT Combustion Liners", AIAA 97-0288.

[20] Defense Systems Management College, "System Engineering Fundamentals," Defense Systems Management College Press, Fort Belvoir, VA, October 1999.

[21] Kirby, M.R., Mavris, D.N., "A Technique for Selecting Emerging Technologies for a Fleet of Commercial Aircraft to Maximize R&D Investment," SAE Paper No 2001-01-3018.

[22] Box, G.E.P., Draper, N.R., Empirical Model Building and Response Surfaces, John Wiley & Sons, New York, 1987.

[23] SAS Institute Inc., JMP, Computer Program and Users Manual, Cary, NC, 1994.

[24] Porter, A.L., et. al., Forecasting and Management of Technology, John Wiley & Sons, New York, 1991.

[25] Martino, J.P., "Forecasting the Progress of Technology," An Introduction to Technological Forecasting, edited by Martino, J.P., Gordon and Breach, London, 1972.

[26] Samaras, D.G., cited in Prehoda, R.W., "Technological Forecasting and Space Exploration," An Introduction to Technological Forecasting, edited by Martino, J.P., Gordon and Breach, London, 1972.

[27] Mankins, J.C., "Research & Development Degree Of Difficulty (R&D3)," White Paper, March 10, 1998.